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Energy performances of intensive and extensive short rotation cropping systems for woody biomass production in the EU

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A B S T R A C T

One of the strategies to ensure energy security and to mitigate climate change in the European Union (EU) is the establishment and the use of short rotation woody crops (SRWCs) for the production of renewable energy. SRWCs are cultivated in the EU under different management systems. Addressing the energy security problems through SRWCs requires management systems that maximize the net energy yield per unit land area. We assembled and evaluated on-farm data from within the EU, (i) to understand the relationship between the SRWC yields and spatial distribution of precipitation, as well as the relationship between SRWC yield and the planting density, and (ii) to investigate whether extensively managed SRWC systems are more energy efficient than their intensively managed counterparts. We found that SRWC yield ranged from 1.3 to 24 t ha^{-1} y^{-1} (mean 9.3 ± 4.2 t ha^{-1} y^{-1}) across sites. We looked for, but did not find a relationship between yield and annual precipitation as well as between yield and planting density. The energy inputs of extensively managed SRWC systems ranged from 3 to 8 GJ ha^{-1} y^{-1} whereas the energy ratio (i.e. energy output to energy input ratio) varied from 9 to 29. Although energy inputs (3–16 GJ $ha^{-1}y^{-1}$) were larger in most cases than those of extensively managed SRWC systems, intensively managed SRWC systems in the EU had higher energy ratios, i.e. between 15 and 62. The low energy ratio of extensively managed SRWC systems reflected their lower biomass yield per unit area. Switching from intensively managed SRWC systems to extensively managed ones thus creates an energy gap, and will require more arable land to be brought into production to compensate for the yield loss. Consequently, extensification is not the most appropriate path to the success of the wide scale deployment of SRWC for bioenergy production in the EU.

Contents

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1. Introduction

In an attempt to lower the EU's reliance on fossil energy sources, to reduce emissions from fossil fuels, and to mitigate climate change, several renewable energy sources have been introduced into the EU market during the last few decades. Woody biomass represents one of the EU's largest potential sources of renewable energy, and the political objectives to increase the share of renewable energy sources in total energy consumption by 2020 are expected to lead to a long-term increase in the European wood demand [1]. Woody biomass comes from a number of sources, including forest residues, mill residues, and urban and municipal waste wood. Another potential source of woody biomass comes from short rotation woody crops (SRWCs) such as poplar (*Populus sp.*) and willow (*Salix sp.*) that are grown on sites that enable a higher productivity using agronomic techniques [2,3].

SRWCs can be grown under different farming systems, from intensively managed to extensively managed plantations. Poplar and willow are two of the few woody crops that have been commercially planted in SRWCs to a significant extent in the EU for the purposes of renewable energy production [4–6]. Currently there are about 50 kha of SWRCs established in the EU [7]. Compared to food crops, SRWCs require low inputs of fertilizers and herbicides, and they grow well on land that is less suitable for agriculture [8]. As there is no annual cultivation cycle, their energy balance is improved compared to traditional agricultural crops. SRWCs have the potential to not only ensure fuel security through the use of the derived biomass for renewable energy production, but also to provide other ecosystem services. When established on previous croplands SRWC plantations store carbon in the soil, improve water and nutrient retention, and decrease the runoff of both sediments and pollutants [9,10]. Other advantages of SWRCs include their increased flora, avian and invertebrate diversity [11–13]. But the overall impact of SRWC production on ensuring energy security and providing additional ecosystem services very much depends on the proper selection of genotypes [14], on the spatial scale of the planting in a specific locality, and on the management practices adopted.

Management practices influence both the final productivity and the energy balance of SRWC systems through the size and the efficiency of the applied farm inputs [15,16]. In the intensively managed SRWC systems, high capital inputs (machinery, agrichemical) and labor generate high yields per unit land area. In the extensively managed SRWC systems the yield is lower because the production methodologies require smaller inputs of labor and capital equipments. However, intensification of agricultural systems in the EU has led to reduced soil fertility, enhanced erosion, reduced wildlife habitats, as well as serious pollution problems [17]. Because of its positive ecological character, extensive farming systems are being portrayed as a way of solving these problems associated with intensive agriculture [18]. The current emphasis on extensive SRWC systems justifies the increased interest in reducing on-farm water and energy use, in protecting the environment, and enhancing the landscape and species diversity. However, it is unclear if extensively managed SRWC systems result in significant energy yields; a precondition that determines the potential for cultivating SRWCs.

A number of studies have compared the energy use in intensively managed and extensively managed food crop production systems [18–27]. These specific studies showed that extensively managed food crop production systems, while not without environmental impacts, are less polluting than intensively managed ones because their impact on the level of biodiversity is lower, and because they demand less energy per unit of area [23–27]. Only one study has so far compared the energy inputs and energy balances of intensively and extensively managed energy crops [28]. For food crops the energy balance is of limited importance since the harvested biomass is primarily determined by its nutrient content rather than by its heating value. But for energy crops like SRWCs the energy balance is of paramount importance [28]. To be a viable substitute for fossil fuels, SRWCs must yield significantly more energy than is required to produce them [28], regardless of the management system adopted. SRWC growers are challenged by the need to identify the management system that maximizes productivity, energy and water use, while maintaining high biodiversity. To evaluate how problematic this challenge is, we compiled all recent available data on SRWC plantations in the EU and used them (i) to review the obtained SRWC yields in the EU and how much they depend on precipitation, planting density; and (ii) to assess and compare the energy balance of intensively and extensively managed SRWC systems in the EU.

2. Database and data treatment

2.1. Database construction of SRWC plantations

We constructed a database of data from past and currently existing SRWC plantations in the EU. The plantations included in the database were identified by (i) doing a search for SRWC production data via the Web of Knowledge; (ii) identifying journal articles that cited original studies or topical reviews; (iii) tracing back papers cited in the bibliographies of the identified studies through (i) and (ii); and (iv) contacting farmers who established and managed commercial SRWC plantations in the EU, or scientists who have worked or are currently working on SRWC production in the EU. We limited our assessment to the EU and selected studies or sites according to the three following criteria: (i) poplar or willow was the main crop; (ii) productivity was measured in the field; and (iii) details on the cultivation techniques and/or the energy inputs were available. An inventory of all data categories and of the key variables that were quantified is shown in Table 1. After the database was completed, the first three authors reviewed all entries in order to detect inconsistencies or insufficient data quality. When aberrant entries were found, we re-contacted the providers of the

Table 1
Overview of the SRWC systems studied.

Latitude	Longitude	Temp (°C)	Prec (mm)	Area (ha)	Age (years)	Density (cutt ha^{-1})	Number of clones	Fertilizer	Irrigation	Yield (t ha^{-1} y^{-1})	Species	Location	Country
37.12 N	03.42 W	15.7	478	2	3	13,333	4	–	+	13.7	Poplar	Granada	Spain[a]
40.40 N	03.68 W	14.1	384	0.3	2	10,000	6	–	+	13.5	Poplar+Willow	Madrid	Spain
41.36 N	02.30 W	10.5	500	3	4	19,700	3	+	+	12.0	Poplar	Soria	Spain [a]
41.50 N	05.53 W	13.64	390	4	3	13,333	4	+	+	7.7	Poplar	Zamora	Spain[a]
41.57 N	12.43 E	15.2	854	2	8	10,000	9	+	+	10.0	Poplar	Bagni di Tivoli	Italy[a]
42.05 N	03.03 E	14.5	550	0.3	2	10,000	6	–	+	15.5	Poplar+Willow	Girona	Spain [a]
42.36 N	06.40 W	13.7	670	2.2	3	13,333	4	+	+	6.9	Poplar	Leon	Spain[a]
42.49 N	01.39 W	12.5	720	3.0	3	20,000	4	–	+	16	Poplar	Navarra	Spain
43.43 N	10.24 E	14.7	791	1.35	15	7142	5	–	+	8.0	Poplar	Pisa	Italy [a]
43.43 N	10.24 E	14.7	791	1.35	15	7142	5	–	+	11.3	Poplar	Pisa	Italy
44.43 N	07.41 E	12.5	700	0.14	9	8333	2 (1+1)	+	+	5.5	Poplar+Willow	Cavallermaggiore	Italy
44.47 N	07.44 E	12.5	700	0.54	9	8333	8 (4+4)	–	–	8.2	Poplar/Willow	Caramagna piemonte	Italy
44.51 N	07.38 E	13.0	650	0.13	9	8333	2 (1+1)	–	–	1.3	Poplar/Willow	Lombriasco	Italy
45.08 N	08.27 E	12.5	700	0.13	9	8333	2 (1+1)	+	+	9.5	Poplar/willow	Casale Monferrato	Italy [a]
45.11 N	10.54 E	13.0	800	0.17	10	8333	1	–	–	4.4	Poplar	Bigarello	Italy
45.13 N	10.15 E	12	745	16	10	5560	2	+	+	16.0	Poplar	Ostiano	Italy [a]
45.13 N	10.15 E	12	745	17	10	5560	2	+	+	20.0	Poplar	Ostiano	Italy
48.31 N	18.08 E	9.8	532	0.1	13	21,000	3	–	–	14.3	Willow	Malanta	Slovakia
49.17 N	15.16 E	7.2	730	0.3	na	12,500	2	–	–	10.2	Poplar/Willow	Nová Olešná	Czech Rep.
49.21 N	12.48 E	5.7	800	0.19	16	2222	9	–	–	3.2	Poplar	Bystřice	Czech Rep.
49.36 N	14.36 E	6.8	650	0.28	16	2222	11	+	–	7.2	Poplar	Smilkov	Czech Rep.
50.03 N	15.42 E	8.5	500	0.07	12	7407	7	–	–	13.2	Poplar	Rosice	Czech Rep.
50.34 N	13.06 E	7	625	4	14	1556	3	–	–	5.6	Poplar	Arnsfeld	Germany
50.57 N	13.17 E	7.2	820	38	3	13,500	3	+	+	10.1	Willow	Großschirma	Germany [a]
50.57 N	13.17 E	7.2	820	38	na	10,317	1	–	–	9.4	Poplar	Großschirma	Germany
50.98 N	13.36 E	7.2	820	2	8	11,850	8 (3+5)	–	–	11.3	Poplar/Willow	Krummenhennersdorf	Germany
51.02 N	03.43 E	9.8	821	0.96	4	6667	4	–	–	3.5	Poplar/Willow	Zwijnaarde	Belgium
51.05 N	04.22 E	11.1	824	0.5	16	10,000	17	–	–	5.2	Poplar	Boom	Belgium [a]
51.06 N	03.51 E	9.5	726	18.4	2	8000	12	–	–	4.0	Poplar/Willow	Lochristi	Belgium[a]
51.06 N	12.06 E	7.8	700	16.5	7	9300	1	–	–	7.8	Willow	Gersdorf	Germany
51.08 N	12.48 E	8.5	580	8.6	5	10,400	1	–	+	14.7	Willow	Zschadrass	Germany
51.08 N	12.50 E	8.5	680	1.6	6	12,083	1	–	–	9.1	Poplar	Commichau	Germany
51.20 N	13.35 E	8.5	575	18	15	2944	4	–	–	2.9	Poplar	Skäßchen	Germany
51.22 N	13.40 E	8.5	575	0.12	na	na	2	–	–	7.0	Poplar	Großthiemig	Germany
51.25 N	12.51 E	8.5	575	11.5	15	3075	4	–	–	7.1	Poplar/Willow	Thammenhain	Germany
51.25 N	14.36 E	8.5	650	3.6	15	2971	3	–	–	2.8	Poplar	Nochten	Germany
51.46 N	14.04 E	8.5	550	0.05	7	27,778	1	–	–	3.4	Poplar	Vetschau	Germany
51.50 N	12.51 E	8.1	690	6	17	3793	4	–	–	12.9	Poplar/Willow	Methau I	Germany
51.50 N	12.51 E	8.1	690	13.4	17	3246	6	–	–	9.2	Poplar	Methau II	Germany
51.50 N	13.12 E	8.5	520	10	5	14,000	6	+	+	5.95	Poplar/Willow	Köllitsch	Germany
52.31 N	05.29 E	9.3	750	4.5	na	17,778	3	–	–	8.0	Willow	Lelystad	Netherlands
53.23 N	11.15 E	8.2	616	n/a	na	25,000	3 (1+3)	–	–	7.7	Poplar/Willow	Kuhstorf	Germany
53.55 N	12.20 E	8	630	3	na	22,000	6	–	–	23.9	Poplar	Laage	Germany
54.41 N	6.6 W	10.1	1050	5.3	21	15,000	6	+	+	11.0	Willow	Loughgall	Ireland [a]
57.22 N	9.48 E	7.3	637	7.3	16	12,000	3	+	–	9.2	Willow	Vråvej	Denmark [a]
59.18 N	25.60 E	4.7	600	0.6	12	20,000	9	+	–	9.1	Willow	Saare	Estonia
59.24 N	17.22 E	5.5	630	3.0	15	11,500	4	+	–	9.5	Willow	Hjulsta	Sweden[a]

Irrigated and/or fertilized sites are classified into intensive short rotation woody crop systems, whereas extensive short rotation woody crop systems exclude both irrigation and fertilization. na: not available.

[a] Subset of sites used for energy analysis.

data (or re-examined the original paper) and corrected the entry. Data were analyzed in two ways: first, we used a regression analysis to assess the relationships between biomass productivity (yields) and a number of selected variables for all SRWC sites from the entire population in Table 1. Secondly, we used a streamlined life cycle analysis to estimate the cumulative energy input, as well as the energy efficiency (i.e. energy ratio, net energy yield) for the subset of SRWC sites (sites marked with † in Table 1) with full data on energy use and management practices. A total of 47 studies were retained for the present analysis, from which 15 also contained the necessary data for the life cycle energy analysis (Table 1).

2.2. Assessment of relationship between biomass yield and selected parameters

We analyzed the relationships between biomass productivity (yield) and precipitation – plus irrigation when applied and available – using a linear regression for the 47 different SRWC plantations in the EU selected for this study. We also assessed the relationship between biomass production and planting density.

2.3. Assessment of the energy performance

2.3.1. System boundary, agronomic data, and assumptions

Fifteen SRWC systems identified in this study had all necessary data for the life cycle energy analysis (Table 2). We first categorized this subset of sites into intensively and extensively managed SRWC systems using indicators such as agrichemical inputs and irrigation (Fig. 1). Each SRWC production chain covers the establishment and cultivation of the SRWC crop, the harvest and storage of the biomass at the farm gate, as well as the removal of the stumps at the end of the plantation (Fig. 1). We then analyzed the amount of primary energy used over the life cycle of the biomass production chain of each SRWC system. The function of each SRWC

Table 2
Materials, diesel consumption and performance of tractors and harvesters used in the management of the subset of SRWC systems subjected to energy analysis.

Activities	Site		Tractor and trailer			Material	Occurrence	Site		Tractor and trailer			Material	Occurrence
	Hj	Weight (ton)	Power (kW)	Speed (h ha^{-1})	Diesel (l ha^{-1})	Input rates (unit ha^{-1})	Frequency (times)	**Lg**	Tot. weight (t)	Power (kW)	Speed (h ha^{-1})	Diesel (l ha^{-1})	Input rates (unit ha^{-1})	Frequency (times)
Plowing		7.4	66	1.6	25.77	–	1		5.2	165	2	7	–	1
Harrowing		6.8	66	0.5	7.21	–	1		9.9	75	2	2.3	–	1
Disking		–	–	–	–		–		–	–	–	–	–	–
Mechanical weeding		–	–	–	–		–		3.2	120	1	2.2	–	–
Chemical weeding		6.2	66	2.5	7.5	4 l gly	6		3.2	120	1	1.2	2.25 kg gly	5
Fertilizing (lime)		–	–	–	–	–	–		4.7	75	2	2.3	3 t	1
Fertilizing (N/P/K)		6.8	66	0.21	4.32	107 kg (N)	4		4.7	75	2	2.8	128/28/178 kg	5
Planting		6.5	66	2	45.25	11,500 cuttings	1		8	120	5	2.8	15,000 cuttings	1
Pest control		–	–	–	–	–	–		–	–	–	–	–	–
Irrigation		–	–	–	–	–	–		–	–	–	–	–	–
Coppicing		6.8	70	0.21	30	–	1		–	–	–	–	–	–
Harvesting/chipping		5.8	70	5	75	–	4		11.7	170	0.72	74.85	–	7
Stump removal		7.7	110	6	38.70	–	1		7.7	110	6	38.70	–	1
	Gi							**So**						
Plowing		3.4	37.5	7	40	–	2		4.2	95	2	18	–	1
Harrowing		3.4	37.5	4.25	32	–	1		4.3	95	1	8	–	1
Disking		4.6	37.5	4.17	20	–	1		–	–	–	–	–	–
Mechanical weeding		3.3	63	3.84	14	–	2		2.6	92	2.5	25	–	–
Chemical weeding		3.3	37.5	1.5	10	5 l oxy	2		3.8	90	0.5	4	4 l oxy, 4 l gly	4
Fertilizing (lime)		–	–	–	–	–	–		–	–	–	–	–	–
Fertilizing (N/P/K)		–	–	–	–	–	–		3.7	90	0.5	4	400 kg (12 N/22 P/22 K) and 230 kg CAN (27%)	5
Planting		4.9	75	8.20	16.3	10,000 cuttings	1		4.1	90	14	98	19,700 cuttings	1
Pest control		3.3	63	1.17	10.5	0.18 kg cyp	2		–	–	–	–	–	–
Irrigation		0.096*	–	74.38	165.5	3397 m^3	3		–	–	–	–	1333 m^3	4
Coppicing		–	–	–	–	–	1		0.009	3	24	48	–	1
Harvesting/chipping		10.8	233	0.62	34.0	–	2		12.5	466	4	160	–	1
Stump removal		7.7	110	6	38.70	–	1		7.7	110	6	38.70	–	1
	Pi							**Ba**						
Plowing		8.9	132	2.2	45	–	1		9.5	80	2.34	46.54	–	1
Harrowing		4.8	110	4.8	30	–	1		9.5	80	0.79	46.14	–	2
Disking		5.7	74	1.12	30	–	1		–	–	–	–	–	–
Mechanical weeding		3.5	37	9	19	–	2		3.5	51	0.7	8.74	–	16
Chemical weeding		3.1	–	–	–	–	–		3.5	51	0.16	2	2 l met+1 l lu	12
Fertilizing (lime)		–	–	–	–	–	–		–	–	–	–	–	–
Fertilizing (N/P/K)		3.0	59	2	18	30 kg N	4		3.5	51	0.45	5.6	500 kg (8/24/24)	6
Planting		3.9	51	4.73	30	7142 cuttings	1		6.1	75	6.05	75.35	10,000 cuttings	1
Irrigation		–	–	4	45	300 m^3	3		–	–	–	–	–	–
Coppicing		–	–	–	–	–	–		–	–	–	–	–	–
Harvesting/chipping		9.3	132	2.4	132	–	5		10.6	130	1.59	122.2	–	4
Stump removal		7.7	110	6	38.70	–	1		7.7	110	6	38.70	–	1
	Bo							**Lo**						
Plowing		7.4	94	0.86	33.2	–	1		9.8	157	0.94	16.66	–	1
Harrowing		7.3	94	0.86	11.8	–	1		7.7	119	0.72	13.15	–	1
Disking		–	–	–	–	–	–		7.7	119	0.68	11.4	–	1
Mechanical weeding		4.5	48	0.44	2.7	–	7		5.5	97	2.76	8.36	–	5
Chemical weeding		4.6	48	0.37	2.8	3 kg gly; 9 kg oxa	6		7.8	119	0.58	6.88	0.3 l Az + 2.5 l Ar	7
Fertilizing (lime)		–	–	–	–	–	–		–	–	–	–	3.5 l gly	–
Fertilizing (N/P/K)		–	–	–	–	–	–		–	–	–	–	–	–
Planting		–	–	–	–	10,000 cuttings	1		5.6	97	3.44	21.04	8000 cuttings	1
Pest control		–	–	–	–	–			0.6	12	5.04	9.84	1 l tom + 1 l mat	1
Irrigation		–	–	–	–	–	–		–	–	–	–	–	–
Harvesting/chipping		8.2	94	16.9	74.9	–	4		14.7	110	1.66	49.47	–	1
Stump removal		7.7	110	6	38.70	–	1		7.7	110	6	38.70	–	1

Vr							**Gr**					
Plowing	9.5	80	2.34	46.5		1	8.11	150	1.85	21.7	–	1
Harrowing	9.9	160	2	6		1	7.81	150	0.78	17.6	–	1
Disking	9.9	160	3	4		1	7.70	150	0.90	10.2	–	1
Mechanical weeding	9.5	160	4	2		5	6.61	90	0.32	5.1	–	2
Chemical weeding	6.7	80	2	1.2	4 l sto	3	5.76	60	0.45	4.9	2 kg gly ai	4
Fertilizing (lime)	6.7	80	2	1.9		1	4.91	60	0.40	2.6	–	1
Fertilizing (N/P/K)	6.7	80	2	1.9	120 kg (21/3/10)	7	4.91	60	0.40	2.6	(90/8/60) kg	3
Planting	7.2	110	2.8	4.2	12,000 cuttings	1	6.24	90	9.33	27.3	13,500 cutting	1
Pest control	–	–	–	–		–	3.32	54	0.26	1.2	0.42 kg	3
Irrigation	6.7	80	1	1		3	3.32	54	0.26	1.2	300 m^3	1
Harvesting/chipping	13.0	110	1.9	14.0		7	12.7	110	1.40	27.4	–	4
Stump removal	7.7	110	6	38.7		1	7.65	110	6	38.7	–	1
Os							**Ca**					
Plowing	8.2	120	1.7	22.9	–	1	11.1	150	3.7	27	–	2
Harrowing	6.1	90	2	26.3	–	1	10.6	150	1.2	24	–	1
Disking	–	–	–	–	–	–	10.1	150	1.8	22	–	1
Mechanical weeding	6.1	90	2.2	28.3	–	5	6.6	90	1	13	–	6
Chemical weeding	5.1	80	0.33	3.7	4 l gly	5	6.6	90	1.2	7	3 kg gly	6
Fertilizing (lime)	9.3	120	0.5	5.5	1 t	1	–		–	–	–	1
Fertilizing (N/P/K)	5.4	90	0.3	3.8	80 kg urea	4	5.4	60	0.8	14	30/44/83 kg	4
Planting	7.4	120	1.42	22.7	5560 cuttings	1	6.2	90	1.8	40	8330 cuttings	1
Pest control	5.1	80	0.3	3.7	2 kg del	5	–	–	–	–	–	–
Irrigation	2.1	–	74.4	6.5	400 m^3	5	–	–	–	–	1500 m^3	4
Harvesting/chipping	13.6	343	1.2	80.6	–	5	16.5	126	1.8	97	–	5
Stump removal	7.7	110	6	39	–	1	7.7	110	6	39	–	1
Le							**Ga**					
Plowing	3.3	66.24	1.45	30	–	1	3.65	66.24	1.3	25	–	1
Harrowing	3.3	66.24	0.7	16	–	1	3.65	66.24	1	20	–	1
Disking	–	–	–	–	–	–	–	–	–	–	–	–
Mechanical weeding	1.7	36.25	1.5	12	–	3	2.18	54.5	0.7	17	–	4
Chemical weeding	1.7	36.25	1	8	4 l oxy	1	2.18	54.5	0.2	6	3 l gly	3
Fertilizing (lime)	–	–	–	–	–	–	–	–	–	–	–	–
Fertilizing (N/P/K)	1.7	36.25	1	8	450 kg (8/15/15)	1	–	–	–	–	–	–
Planting	5.0	75	4.5	17	13,333 cuttings	1	5.0	75	4.5	17	13,333 cuttings	1
Pest control	1.7	36.25	1.7	20	0.5 del	1	–	–	–	–	–	–
vIrrigation	–	–	–	210	1333 m^3	3	–	–	–	–	1667 m^3	3
Harvesting/chipping	11.5	123	1	36	–	1	12	142	2	37	–	1
Stump removal	7.7	110	6	39	–	1	7.7	110	6	39	–	1
Za												
Plowing	5.8	108.7	2	30	–	2						
Harrowing	5.8	108.7	1	14	–	3						
Disking	–	–	–	–	–	–						
Mechanical weeding	1.6	21.75	3	17	–	8						
Chemical weeding	1.6	21.75	0.6	3.6	4 l (oxy+gly)	4						
Fertilizing (lime)	–	–	–	–	–	–						
Fertilizing (N/P/K)	1.6	21.75	0.8	4.4	235 kg (15/15/15)	6						
Planting	5.0	75	4.5	17	13,333 cuttings	1						
Pest control	1.6	21.75	0.6	3.6	1.5 l ch l	5						
Irrigation	–	–	–	–	1890 m^3	3						
Harvesting/chipping	11.5	123	1	36	–	1						
Stump removal	7.7	110	6	39	–	1						

Ba = Bagni di Tivoli (IT), Bo = Boom (BE), Lo = Lochristi (BE), Ca = Casale Monferrato (IT), Ga = Granada (ES), Gi = Girona (ES), Gr = GroBschirma (DE), Hj = Hjulsta (SE), Le = Leon (ES), Lg = Loughgall (IR), Os = Ostiano (IT), Pi =Pisa (IT), So = Soria (ES), Vr = Vravej (DK), Za = Zamora (ES).
Chl: chlorpyrifos, del: deltamethrin, oxi: oxyfluorfen, gly: glyphosate, sto: stomp, oxa: oxadiazon, Az: AZ500, tom: tomahawk, mat: matrigon, Ara: aramo, met: metolachlor, CAN: calcium ammonium nitrate.

system is to produce a certain amount of woody biomass. Since the available land area for the production of woody biomass chips is the principal limitation for SRWC production, we defined the functional unit as 1 ha of land. Primary data were collected on site or from the literature (Table 2), whereas secondary data were based on the Ecoinvent v2.0 database [29]. The agronomic data were supplemented with data on the production of SRWC cuttings which were derived from [8]. Our analysis only focused on the energy inputs and the energy balance of the 15 SRWC systems. We assumed that the production of SRWC cuttings was the same across the EU, although some differences in management practices during the production of SRWC cuttings might be noted.

2.3.2. Energy input

For every single SRWC production system we considered the direct (diesel, oil, lubricants, electricity) and indirect (agrichemicals, cuttings, farm tractors and implements) consumption of non-renewable energy resources. In the analysis we also included the energy use for extracting, producing and distributing diesel, lubricants, and agrichemicals consumed during the SRWC production. In line with previous studies [30] solar energy, which drives the build-up of biomass, was excluded from the analysis. Solar energy is not depleted during the production process and is independent of the management applied. Similarly, energy input from labor was excluded from the analysis because it is usually insignificant compared to other inputs such as fertilizers [16]. Finally the energy associated with the production of capital equipments (i.e., buildings, office, roads, farm shelter) was excluded from the analysis. The direct energy input was calculated based on the diesel consumption rate, the speed (i.e. h ha^{-1}), and the frequency of the use of tractors to perform a given farm operation. The indirect energy input of farm equipment was calculated based on the energy expended in the manufacturing of farm machinery, and the weight, lifetime, and the frequency of use of the farm equipment. For herbicides and fertilizers the indirect energy input was estimated based on the embodied energy of agrichemicals, the average application rates, and the frequency of herbicide/fertilizer application at each SRWC site. A similar approach was used to estimate the indirect energy input of the production of cuttings. The energy input from irrigation was calculated based on the applied amount of water, and the embodied energy of the irrigation. For each SRWC site, the total annual non-renewable energy input was calculated as the sum of all annual direct and indirect energy inputs to cultivate the SRWC crop and store the produced biomass at the farm gate.

2.3.3. Energy output and balance

The production of biomass from SRWC does not generate any co-products; therefore we restricted the energy output to the energy content of the produced biomass. The annual energy output was calculated as the product of the average yield and the lower heating value (18.2 GJ ton^{-1} [30]) of the produced woody chips. We calculated the energy efficiency (i.e. energy ratio) of the SRWC systems as the ratio of the yearly energy output to the total non-renewable energy consumed to produce the yearly amount of woody biomass. Besides the energy ratio, we also estimated the net energy yield as the difference between the energy output and the total energy input. The calculation of the energy balance was carried out using an Excel spreadsheet.

3. Results

3.1. Biomass yield versus planting density and precipitation

The compiled database covers 47 SRWC sites across 11 EU member states (Table 1). Poplar is mainly grown in the central and southern part of Europe, while willow is primarily planted in the northern part of Europe. In some sites and countries both poplar and willow are planted. Most sites are multiclonal and consist of a mixture of pure species and hybrids of either poplar or willow. In some sites both fertilizer and irrigation were applied whereas in others either only fertilizer or irrigation was applied (Table 1). The planting density ranged from 1500 to 28,000 cuttings ha^{-1} and the yield varied from 1.3 to 24 t ha^{-1} y^{-1} with a mean biomass yield of 9.3 $\pm$ 4.2 t ha^{-1} y^{-1}. Although $\sim$13% of high yield observations (i.e. $\geq$9.3 t ha^{-1} y^{-1}) come from sites with a planting density greater than 15,000 cuttings ha^{-1}, there was no significant correlation (r^2=0.085; P=0.066) between planting density and SRWC yield (Fig. 2a). This suggests that biomass yields were not particularly sensitive to initial planting densities. Contrary to our expectation, there was also no relationship between SRWC yield and annual average precipitation (Fig. 2b). The correlation coefficient was very small (r^2=0.004; P=0.696), suggesting that annual precipitation was a relatively poor indicator of SRWC yield across sites.

3.2. Energy inputs, energy outputs and energy balance

The energy inputs for the production and harvesting of woody biomass of the 15 selected sites are shown in Fig. 3. The sites differ in the number of energy consuming operations due to different management regimes and soil conditions (Fig. 3). The energy inputs in the intensively managed SRWC sites ranged from $\sim$3 to 16 GJ ha^{-1} y^{-1}, whereas in the extensively managed SRWC sites, the energy inputs varied from 3 to 8 GJ ha^{-1} y^{-1} (Fig. 3a). In the intensively managed sites, fertilization accounted for 13–58% of the total energy inputs, followed by irrigation (5–37%), and harvesting (5–35%). The most energy consuming activities in the extensively managed sites were weeding and harvesting, which contributed 46–58% and 12–29% of the total energy inputs, respectively (Fig. 2b). This clearly showed that fuel use, use of agrichemicals (especially fertilizers), and irrigation water were the main drivers of the energy inputs during SRWC production. In both intensively and extensively managed SRWC systems, planting, stump removal, and soil preparation were the least energy consuming processes across all sites. In general these activities occurred only once or a few times during the entire lifetime of a SRWC plantation. Their contribution to the total energy inputs ranged from 1 to 8% for planting, 2 to 11% for stump removal, and 1 to 35% for soil preparation

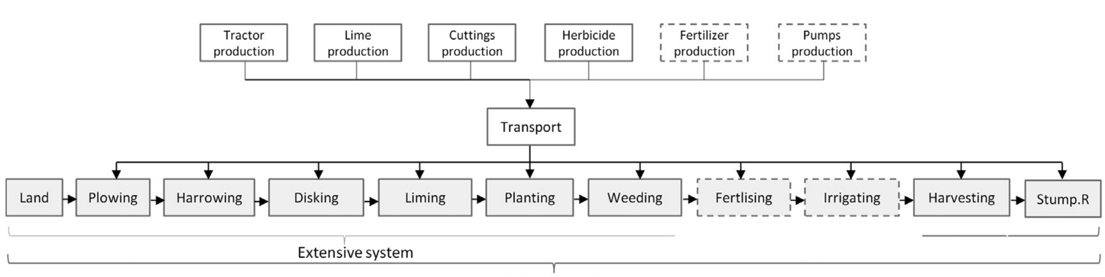

Fig. 1. System boundary of the studied SRWC systems. The boxes represent farming activities and the arrows represent the material and energy flow R=removal.

across all SRWC sites (Fig. 3b). The contribution of the production of the cuttings depended on the planting density of the different sites and ranged from 3 to 18% of the total energy inputs (Fig. 3b). In fact, sites with high planting densities had higher energy inputs for this unit process whereas sites with low planting density required much lower energy inputs for the planting. Overall, the total energy inputs of the 15 studied sites varied from 3 to 16 GJ $ha^{-1}y^{-1}$ (Fig. 3a).

The energy outputs of the studied sites were determined by the yearly amount of harvestable woody biomass and varied from 127 to 364 GJ $ha^{-1}y^{-1}$ for intensively managed systems, and from 73 to 97 for extensively managed systems (Fig. 4). Extensively managed SRWC systems yielded 73–79% less net energy than intensively managed ones (Fig. 4). This difference may be explained by the application of fertilizers and irrigation water which promote plant growth and therefore increase the annual biomass yields in intensively managed SRWC systems. Differences in soil conditions, weather and other factors unrelated to fertilizers and water use may have also been partially responsible for the low biomass yields, and thus the low energy outputs, of extensively managed SRWC systems (Table 1).

The energy ratios for intensively managed SRWC systems ranged from 15 to 62, whereas for the extensively managed systems, the energy ratios varied from 9 to 29. Thus, the energy consumed in producing woody biomass and storing it at the farm gate amounted to only 2–11% of the energy contained in the biomass, regardless of the management systems. The higher energy ratios of intensively managed systems reflected their high biomass yield compared to the extensively managed SRWC systems. For comparable yields, SRWC systems with shorter total lifetime resulted in lower net energy and smaller energy ratios relative to sites with a longer total lifetime. For example, both the net energy and the energy ratios of the plantation in Lochristi (Belgium) having a total lifetime of two years were lower than those of the plantation in Boom (Belgium) which had a total lifetime of 16 years (Fig. 4). Similar conclusions can be formulated for the site in Girona (Spain) as compared to the site in Vravej (Denmark) (Fig. 4). This result showed that the energy benefits of SRWC systems occur over the multiple rotations of these systems. Indeed, the longer the total lifetime, the higher both the net energy yield and the energy ratio.

When sites with an identical total lifetime were considered, the intensively managed SRWC systems had a higher net energy yield and higher energy ratios than the extensively managed ones. For example the energy ratio of the site in Vravej (Denmark) was 2.4 times higher than the energy ratio of the extensively managed site in Boom (Belgium). The same was true for the site in Girona (Spain) as compared to the site in Lochristi (Belgium; Fig. 4). This last result suggested that switching from an intensive system to an extensive system may create an energy gap. Overall, the net energy yield of the studied sites varied from 65 to 355 GJ ha^{-1} y^{-1} (Fig. 4). This translates to ~2 to 12 t of coal saved annually per ha of SRWC planted if an energy density of 29.3 GJ t^{-1} is assumed for coal. Biomass from agriculture is expected to increase from 12.8 Mtoe in 2010 to 36.3 Mtoe in 2020 [31]. Assuming a growth rate of 2.4 Mtoe y^{-1} between the two periods and considering the net energy yield values above, an agricultural land area of 0.3–1.5 Mha would be needed to meet the demand of solid biomass for electricity and heating in 2020. This implies that 0.6 Mt to 18 Mt of coal could be saved annually depending on the type of SRWC system adopted.

4. Discussion

4.1. Effects of planting density

In general, at higher planting density primary growth is promoted at the expense of secondary growth as a result of increased competition for light [32,33]. Bergante et al. [34] reported that the highest biomass yield was observed at a planting density of ≤ 10,000 poplar/willow cuttings per hectare. Our results – based on the 47 sites that we inventoried – did not show any relationship between biomass yield and planting density. The reasons for this lack of correlation might be the heterogeneity of the genetic poplar/willow materials which are being compared as well as the differences in management (tilling, fertilisation, irrigation, pest control) and in site conditions (soil quality, climate). Other issues that might further explain the lack of correlation are the differences in mortality and harvest cycles (biennial harvest, triennial harvest) at the different sites. Regardless of the planting density, the overall average biomass yield of the inventoried SRWC systems was 9.3 t ha^{-1} y^{-1} which was still far below the 12 t ha^{-1} required to be economically viable [35].

4.2. Effects of water availability

Water availability represents one of the main factors influencing biomass yield in SRWC systems [36–40]. The water use by SRWC is substantially higher than that of traditional agricultural crops or grasslands: according to some authors the large expansion of the SRC plantations can have detrimental impacts on the regional water budget [41–43]. These authors concluded that water availability constitutes one of the main constraints for biomass yields and for the profitability of SRWCs grown on arable land with an inaccessible water table. However, according to other studies [44–47] water consumption by SRWCs is comparable to, or lower than, agricultural crops, grasslands, and comparable to, or even lower than, the reference crop evapotranspiration [36].

In a stepwise regression analysis to identify the environmental factors that affect plant survival and biomass productivity of poplar in 180 experimental fields in Italy, Bergante et al. [34] reported that water availability (both expressed as annual precipitation or precipitation during the growing season during the first two years after planting) was the main factor influencing biomass production. The lack of correlation between precipitation and SRC yield in our study does not call into question the fundamental importance of precipitation for biomass yield. Rather it indicates that its relative influence may vary, possibly due to differences in soil texture, cuttings genetics, and producer-level management techniques.

4.3. Energy inputs and energy balance

We showed that fertilisation, irrigation, harvesting, and weeding were the largest and most significant energy consuming activities in the production of woody biomass from SRWCs across the subset of 15 sites presenting data for energy analysis (Fig. 3). This finding was expected because these activities were carried out frequently during the total lifetime of the examined SRWC systems, and because of the combined effects of the amounts of fuel and agrichemical inputs (fertilizers and herbicides), and the size of the equipment used to perform these management activities. The findings also corroborated and extended the results of previous studies that stated that fuel consumption and fertilizer use dominate the energy inputs in SRWC systems, accounting for between 55 and 85% of the total energy inputs [48].

It is possible to increase the efficiency of direct and indirect energy use in intensively managed SRWC systems without lowering the yield. Tillage is a very time demanding, machine based and fuel consuming process. Reducing the frequency and intensity of tillage operations can lower the energy input and therefore improve the energy ratio. Nitrogen addition rates in fertilized sites ranged from 2–12 kg N t^{-1} biomass, assuming that only 75% of the applied N is absorbed by the crop [49], the total energy inputs of the sites where N fertilizers were used could be reduced by

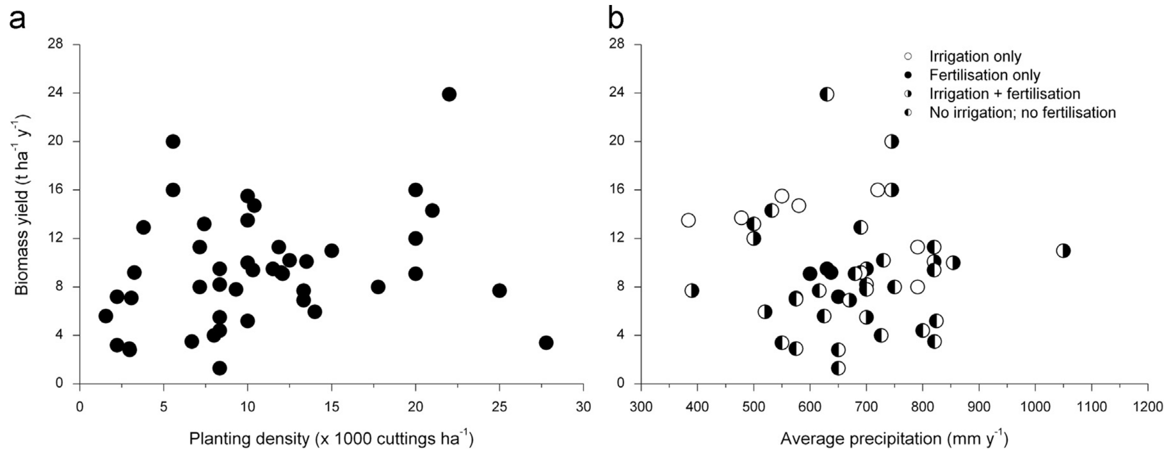

Fig. 2. Relationship between productivity and environmental/management factors. Left (a) panel: relationship between yield and precipitation. Right (b) panel: relationship between yield and planting density.

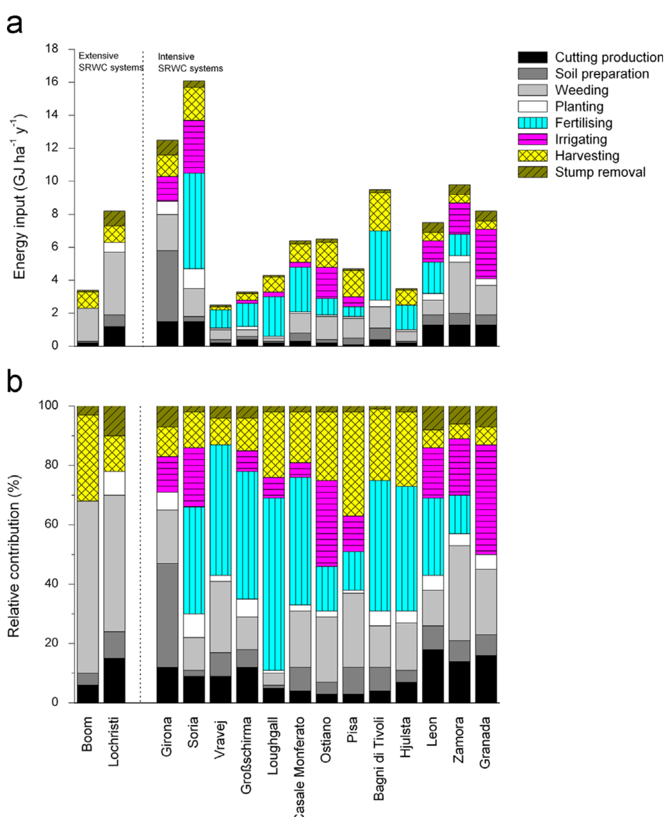

Fig. 3. Energy inputs and relative contribution of each farm activity to total energy inputs of the subset of SRWC systems subjected to energy analysis. Top panel: energy inputs of each SRWC system, Bottom panel: relative contribution to total energy inputs of each farming activity.

4–10% without affecting the biomass yield of those sites. Another option is to apply fertilizers in the establishment season rather than making it an annual event. In experimental settings in the United Kingdom, Metcalfe and Bullard [50] demonstrated that the energy ratio is improved by 80% over the lifetime of the SRWC systems when fertilizer is applied at the establishment year. Similarly, the substitution of energy intensive mineral fertilizer (e.g. urea) by the less intensive ones (e.g. ammonium nitrate) would improve the energy ratio while reducing at the same time the amount of NH_3 volatilization [51]. Although organic fertilizer such as cattle manure is less energy intensive compared to mineral fertilizers (urea, ammonium nitrate) substituting organic fertilizer for mineral fertilizer in intensive SRWC systems can create a mixed effect. It reduces the energy inputs per ha, but also the dry matter yield, therefore reducing (or making no change in) the energy ratio, and increasing the land use.

To give an idea of the energy performance of SRWC systems relative to other energy cropping systems, we compared our findings to those of other cradle-to-farm gate LCA studies on perennial energy crops. Monti et al. [52] performed a comparative LCA on perennial energy crops. They reported the energy ratio values of 33 for giant reed, 25 for miscanthus, 21 for switchgrass, and 8 for cynara cropping systems. For eucalyptus cropping systems in France an energy ratio of 37 has been reported [53]. These values fell below or in the middle of the range of energy ratio values (i.e. 29–62) found in our study for the old SRWC systems, thus placing poplar and willow among the most energy efficient perennial energy crops. The lower energy ratio values (i.e. 9–30) reported in our study corresponds to those of the six young SRWC systems having a single two or three-year rotation with only one harvest. The estimated energy ratios of SRWC systems in this study fell in most cases within the range of values (13–79) reported by Djomo et al. [54]. They were also in agreement with that of a recent analysis on energy balance and GHG emissions of willow in the USA [55].

In addition to ensuring energy security as shown in this study, SRWC systems can also improve species richness and/or increase abundance for many organisms including plants, birds, mammals, and arachnids [56]. Biodiversity responses to SRWC systems depend on the types of habitat displaced [57], as well as on the management practices used. Unfortunately, to date, there is no published empirical data in the literature regarding the effects of management practices on biodiversity in SRWC systems. However, in food crop systems, it is often observed that shifting from intensive to extensive farming increases biodiversity while decreasing yield [58]. This suggests that maintaining a high biodiversity would require larger areas to be cultivated to meet any given production target. Both intensive and extensive SRWC systems are often more diverse than croplands which they replace [10], but extensive SRWC systems result in a lower net energy gain due to lower yields. Hence, if both the energy production target and biodiversity goal should be met, intensive SRWC systems should preferably be adopted because of their potential (i.e. high yield) to reduce land usage and to avoid converting the remaining intact habitats.

Despite their potential to ensure energy security and to increase biodiversity the deployment of SRWCs in the EU is low. One reason is the high production costs of SRWCs relative to fossil fuels such as coal [59]. The absence of a network of SRWC suppliers, the inefficient and inadequate infrastructure (e.g. harvesters, transport), as well as

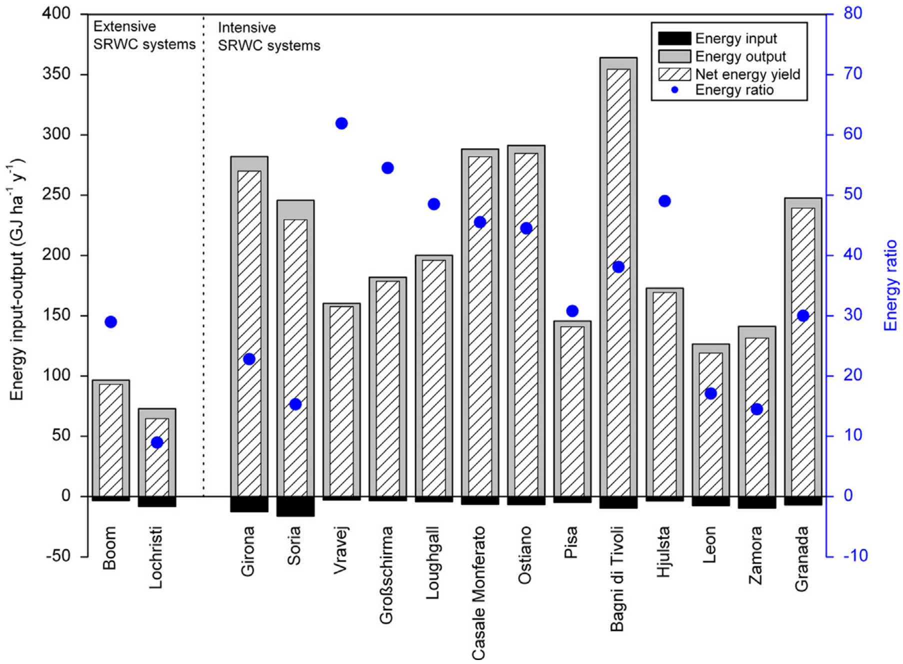

Fig. 4. Energy input-output and energy efficiencies of the subset of SRWC systems subjected to energy analysis.

the unclear policy environment about the direction and the long-term commitment to supporting the growth of energy crops are other reasons of the low deployment of SRWCs. Improvement in breeding can reduce the production costs of SRWCs [60]. The inclusion of the cost of carbon emissions in the price of fossil fuels (e.g. coal) and the attribution of a tax credit to SRWCs for the biological storage of carbon in croplands are also other strategies that could narrow the cost gap between SRWCs and fossil fuels.

5. Conclusion

Our study showed that biomass from SRWCs is a viable energy alternative to fossil fuels. However, contrary to the intuitive opinion, we showed that extensification is not the most appropriate path to the success of the wide scale deployment of SRWCs for bioenergy production in the EU. The adoption of an extensively managed system can cause an energy gap which in turn requires more arable land to be brought into production to compensate for the reduction in yield and therefore energy.

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